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REPORT TITLE: PRELIMINARY DEVELOPMENT OF A SOLID PISTON MICRO-ENGINE

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SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

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13. ABSTRACT (Maximum 200 words)

A solid piston micro-engine has been proposed based on the following operating principles. A fuel-air delivery system alternately supplies air and premixed fuel and air to a catalytic combustor, wherein the fuel-air mixture is catalytically reacted to produce a periodic flow of low and high temperature gas over a solid-piston actuator, alternately heating and cooling the actuator (solid piston). Periodic thermal expansion and contraction of the piston is used to drive a piezo-electric transducer, whereby the mechanical energy is converted to electrical energy. Although thermal actuators have been studied by a number of researchers, to the best of our knowledge this will be the first application of a solid thermal actuator in a micro-engine, as well as the first use of a periodic combustion-driven thermal actuator. First-order analyses of the individual subsystems and their integration into the proposed micro-engine are in progress. The design has been modified based on current analyses. Fabrication of the first-generation prototype is underway; subsystem testing plans have been developed and equipment required for performing subsystem experiments has been purchased and assembled. The experiments will be conducted within the next 6 months, and the outcome of these experiments will be assessed in terms of the effects on full prototype operation and concept verification.

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(3) List of Figures

List of Tables

(4) Statement of the problem studied:

A number of innovative research programs aimed at developing miniaturized high-energy density power generation are well underway, including development of a micro-turbine [1], micro-fuel cells [2,3], mini- and micro-scale rotary engines [4,5,6], microscale Brayton and Rankine Cycle engines [7], an on-chip electrostatic micro-engine [8], and a piezoelectric membrane-driven MEMS power source [9]. Funding was provided through the STIR program for preliminary development of a solid piston micro-engine. During the grant period, the research focused on the design, fabrication and test plan formulation for four major subsystems of the Penn State Solid Piston (PSSP) micro-engine, i.e., the fuel-air delivery system, the catalytic combustor, the solid piston actuator and the piezo-electric transducer. In the coming months, the subsystems will be tested using the test plans and equipment developed and purchased under the STIR program. Additional funding will be pursued, e.g., through the ARO YIP and other DoD programs, to continue testing of the fully-integrated prototype, investigate design modifications and upgrades with an emphasis on miniaturization, and to pursue strategies for batch fabrication.

The basic operating principle of the PSSP micro-engine is as follows. A fuel-air delivery system alternately supplies air and premixed fuel and air to a catalytic combustor, wherein the fuel-air mixture is catalytically reacted to produce a periodic flow of low and high temperature gas. The flow then passes over a solid piston actuator, alternately heating and cooling the piston. Periodic thermal expansion and contraction of the piston is used to drive a piezo-electric transducer, whereby the mechanical energy is converted to electrical energy. Although thermal actuators have been studied by a number of researchers, to the best of our knowledge this will be the first application of a solid thermal actuator in a micro-engine, as well as the first use of a periodic combustion-driven thermal actuator.

During the grant period, the first-generation subsystems were designed and fabricated for inclusion into the full micro-engine prototype. A set of flow experiments has been designed using the subsystem components and a micro-engine in test configuration in order to 1) calibrate the pulsed fuel valve, 2) evaluate the fuel-air composition as a function of time within the combustion chamber, 3) determine the temporal response characteristics of the thermal actuator, 4) determine the catalytic ignition temperature as a function of flow conditions and fuel-to-air ratio, and 5) evaluate the temperature at the proposed piezo mounting location. The equipment required to conduct this set of flow experiments has been purchased and assembled and the flow experiments will be performed shortly. Initial experiments have already been performed to evaluate the material characteristics of the selected piezo-electric slug when used in an energy-generating configuration.

(5) Summary of most important results:

<u>Design evolution</u>

The original conceptual design is shown in Figure 1.

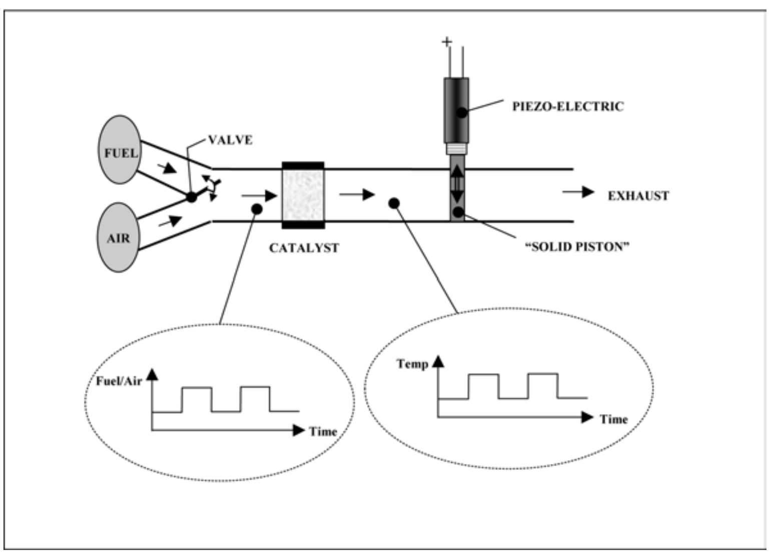

Figure 1: Original solid piston micro-engine design concept

During the award period, a systems analysis was performed on the individual subsystems, and the critical design issues were identified for each of the subsystems. The design has been modified based on the current analyses, and is shown in Figure 2.

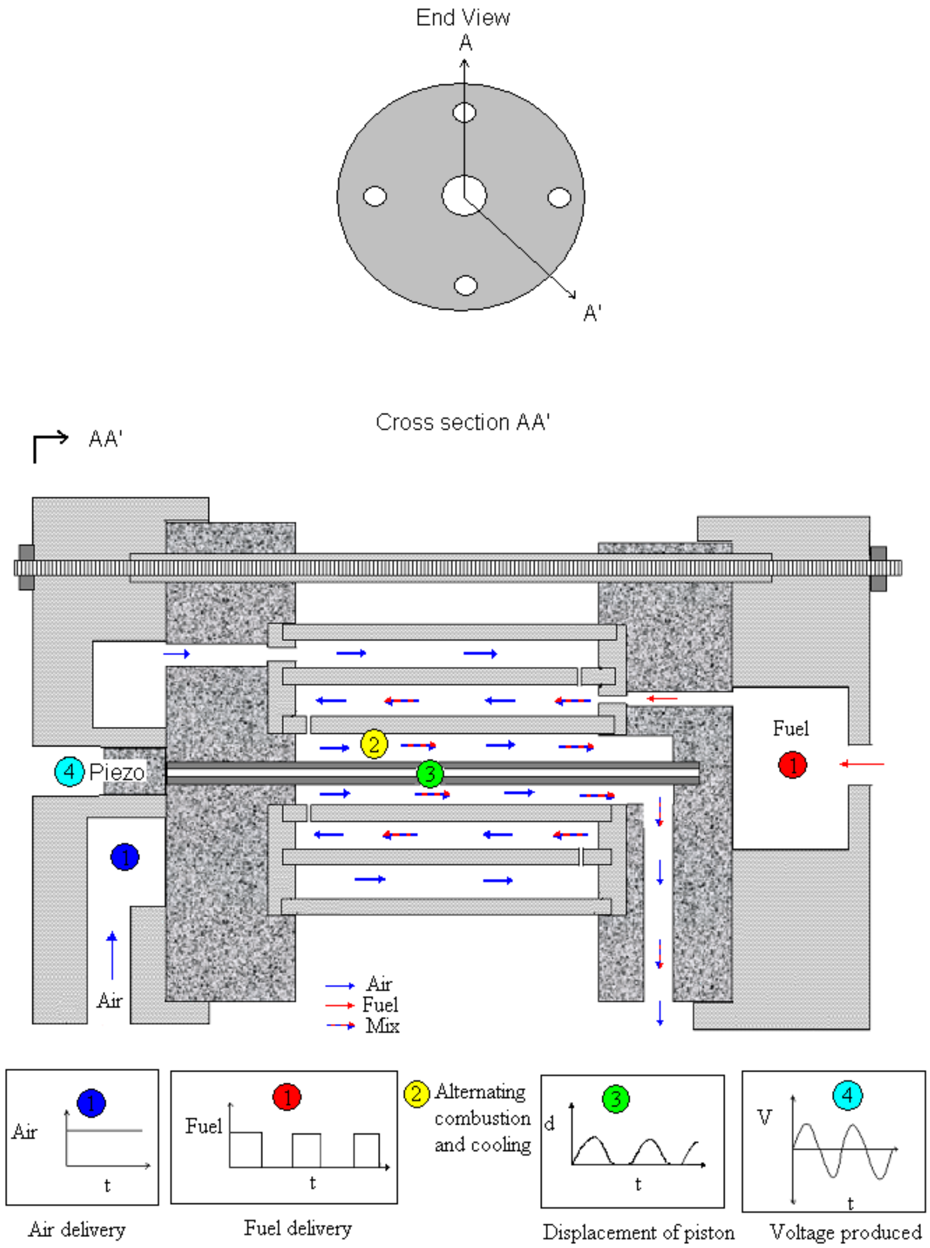

Figure 2: Modified design based on system and subsystem analyses

The main features of the design shown in Figure 2 are

1. A constant air flow through the "donut-shaped" air manifold serves to cool the piezo-electric transducer. Pulses of fuel are delivered through the fuel manifold. Downstream of the air manifold, the air and fuel-air mixture flow through concentric annular passageways where it is preheated before entering the catalytic combustor – this is necessary to ensure that the temperature of the fuel-air mixture entering the combustor is above the catalytic ignition temperature.
2. Within the combustion chamber, periodic combustion alternately heats and cools the thermal actuator.
3. The catalyst serves two functions, i.e., it enables combustion and it acts as the thermal actuator. The catalyst is a hollow tube rather than a solid rod to minimize the amount of energy required to achieve a given temperature increase – this also reduces the amount of heat transfer through the ends of the catalyst to the end plates. Ceramic plates on both ends of the micro-engine serve to thermally insulate the micro-engine.
4. The alternating expansion and contraction of the thermal actuator produces a periodic force on the piezoelectric slug and thus creates an output voltage signal.

Although not shown in Figure 2, ignition and start-up is accomplished by resistively heating the catalyst tube to a temperature greater than the catalytic ignition temperature until the system reaches a self-sustained operating condition.

<u>Results of analysis:</u>

The design and performance analysis of the solid piston micro-engine is based on the design parameters and operating conditions listed in Table 1.

Fuel	Hydrogen
Equivalence Ratio	0.5
Fuel Flow Modulation Frequency	10 Hz
Fuel Flow Modulation Duty Cycle	50%
Thermal Actuator	Hastelloy C-276 coated with 2 micron thick layer of platinum
Thermal Actuator Dimensions	I.D. = 1.07 mm, O.D. = 1.57 mm, Length = 25.4 mm
Preheat Air Temperature	500 K
Catalyst Min/Max Temperatures	600 K / 700K
Catalyst Heating Efficiency	50%

Table 1. Design parameters and operating conditions

Based on the thermal actuator tube dimensions given in Table 1, a 100 K thermal actuator temperature modulation and the mechanical properties of Hastelloy, the force exerted by the thermal actuator, if constrained on both ends, is given by the following equation:

$$F = \sigma A = \alpha E \Delta T A$$

where α is the linear thermal coefficient of expansion of the material, σ is the thermal stress, E is Young's modulus, ΔT is the temperature change, and A is the cross-sectional area of the thermal actuator tube. Using appropriate values for α and E for Hastelloy along with the prescribed temperature change and tube dimensions (ref. Table 1), preliminary calculations predict a force of approximately 100 N. (This is well below the force required to buckle the tube.)

When the piezo-electric transducer is installed it will be preloaded, i.e., the thermal actuator tube will be in compression, therefore most of the force produced by the temperature increase of the thermal actuator will be transmitted to the transducer through the ceramic insulator. Preliminary calculations of open-circuit voltage obtained from the piezoelectric slug, based on measured and known properties of the slug, do not appear reasonable and are inconsistent with the preliminary measurements of voltage obtained from the slug under approximately 20N of force. Further testing and analysis is required to provide a more accurate estimate of achievable force and power output.

Subsystem experiments and prototype status

An external fuel-air delivery system has been designed and assembled. A schematic of the fuel-air delivery system is shown in Figure 3.

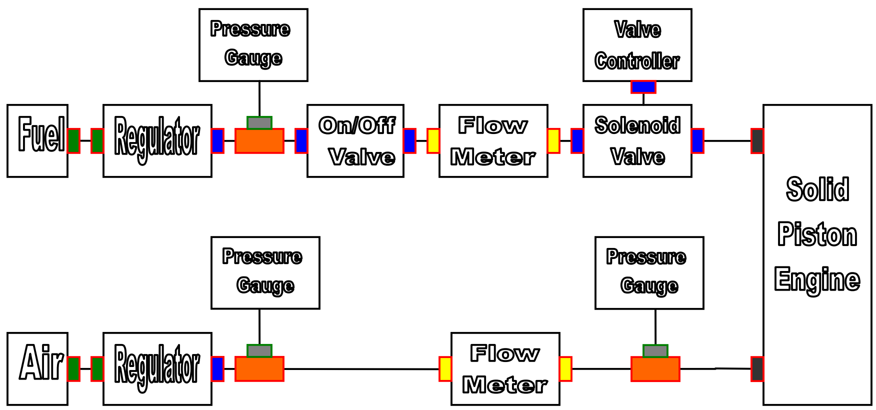

Figure 3: Schematic of external fuel-air delivery system

The planned flow experiments are:

1. Determine the mass of fuel per pulse delivered by the solenoid valve. This set of experiments will use the external fuel delivery system in conjunction with a bubble meter to measure the mass of fuel contained in each fuel pulse. This calibration of the valve will allow a known amount of fuel to be released during a given time period in order to provide a known equivalence ratio for combustion.
2. Acquire hot-wire data within combustion chamber during standard operating conditions (pulsed fuel delivery and constant airflow). The external fuel-air delivery system shown in Figure 3 will be connected to a micro-engine prototype in a test configuration suitable for the flow experiments. The test configuration prototype allows hot-wire access through the endplate which will later house the piezo-electric element, and the thermal

actuator/solid piston will be removed in order to allow the hot-wire anemometer to be inserted directly into the combustion chamber. The hot-wire will be used to detect changes in both velocity and flow composition, thereby providing quantitative data on the mixing characteristics and gas flow composition as a function of time. In order for the PSSP to operate as intended, pulses of air and air/fuel mixture must be delivered periodically to the combustion chamber to enable periodic combustion and corresponding expansion/contraction of the thermal actuator. The hot-wire measurements will allow for assessment of the periodicity of the air and air-fuel mixture flow at the entrance of the combustion chamber.

3. Determine the thermal response characteristics of the thermal actuator. In these tests, the thermal actuator will be resistively heated to its expected maximum temperature, i.e., 700K, while air preheated to a temperature of 500K will be flowing through the micro-engine. At time $t = 0$ the electrical energy used to maintain the thermal actuator temperature at 700K will be turned off and the temperature of the thermal actuator as a function of time will be measured using thermocouples. In this manner the time required for the temperature of the thermal actuator to reach 600K will be determined. These measurements will be carried out over a range of flow conditions and thermal actuator dimensions and the results will be compared to predictions. This analysis will be used to modify the design of the prototype micro-engine to achieve the desired 10 Hz operating frequency.
4. Determine the catalytic ignition temperature as a function of the flow conditions and the equivalence ratio. In these tests, the air will be preheated with an electrical heater and the fuel will be supplied continuously. For fixed flow conditions and equivalence ratio the air temperature will be increased until ignition occurs, as evidenced by a marked increase in the gas temperature at the exit of the combustion chamber. This information will be used to optimize the design the regenerative heating portion of the micro-engine to ensure that the fuel-air mixture enters the combustion chamber at a temperature which will achieve rapid ignition and thereby allow for sustained operation of the micro-engine.
5. Evaluate the temperature at the proposed mounting location for PZT element by acquiring data from a thermocouple at this location during tests (3) and (4). If the temperature at the piezo mounting location exceeds 327K, the ceramic insulator design

will be modified until the temperature at this location remains within the operating limits of the PZT slug.

Figure 4 shows the current micro-engine prototype (in flow test configuration). This prototype will be used in the previously outlined set of flow experiments.

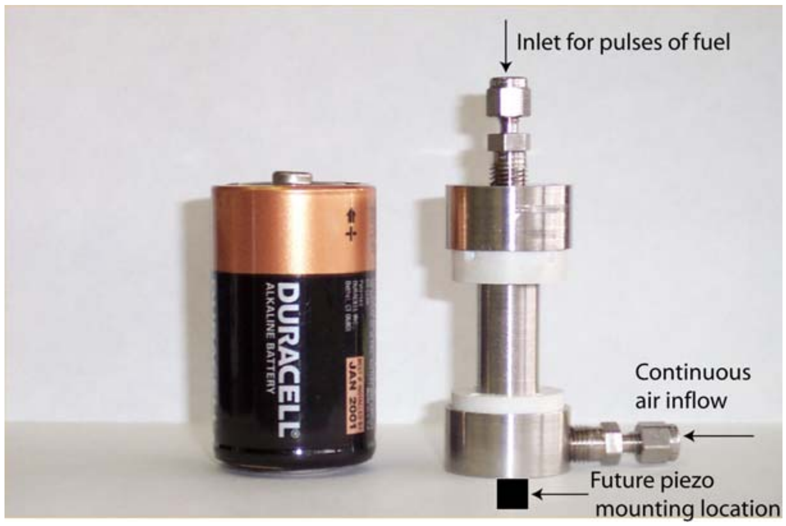

Figure 4: Current PSSP prototype

All of the required equipment and instrumentation has been purchased and assembled in preparation for carrying out these experiments.

Several different piezoelectric element configurations were considered for the mechanical-to-energy conversion subsystem. Given the predicted force loading, a piezo-electric "slug" of lead zirconate titanate (PZT Navy Type II) shown in Figure 5, will be used in the first-generation prototype. A standard test has been performed to measure a constant (d_{33}) which, when combined with known PZT material constants, is used to relate applied force to output voltage. The d_{33} constant for the current PZT slug is 445.4×10^{-12} C/N. A second test was performed to verify the output voltage for an applied 20N force, but the accuracy of the results is not sufficient and additional testing is advised.

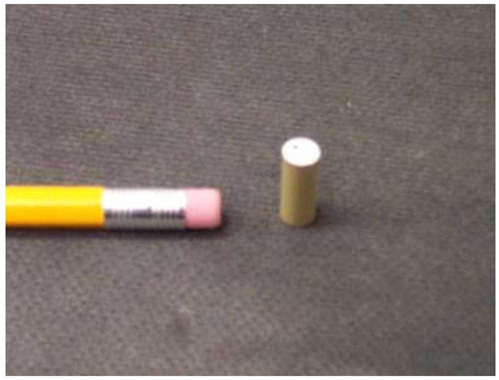

Figure 5: Piezoelectric slug (Mechanical-to-Electrical Energy Conversion Subsystem)

Future Work

Future work includes completing the set of proposed flow experiments with the existing equipment and prototype; demonstrating combustion within the micro-engine; and mounting the piezo-electric element to the micro-engine presuming that the temperature at mounting location can be maintained below the maximum operating temperature for the piezo-electric slug. A mounting mechanism for this piezo-electric slug has been designed. Concurrently, further verification and extension of the analysis will be pursued.

In the longer term, the PIs plan on pursuing a second-generation design for a micro-engine, with an emphasis on miniaturization and increases in efficiency. Further miniaturization will likely require pursuing a planar geometry in order to leverage current microfabrication techniques and available resources.

(6) Publications resulting from the grant:

(b) Paper to be submitted for conference proceedings (Abstract accepted, awaiting review of Extended Abstract): Santavicca, D., Sharp, K., Hemmer, J., Mayrides, B., Taylor, D. and J. Weiss, “A Solid Piston Micro-engine for Portable Power Generation,” IMECE 2003-41132, Extended abstract submitted to ASME IMECE 03, Washington, DC, November 2003. *Conference paper to be submitted August, 2003.*

(7) List of participating scientific personnel:

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J. Hemmer, undergraduate Honors student*

B. Mayrides, undergraduate Honors student*

D. Taylor, undergraduate Honors student*

J. Weiss, undergraduate Honors student*

***Each Honors student submitted an individual Senior Honors thesis to the Schreyer Honors College at PSU documenting his portion of the project in May 2003.**

(8) Inventions: None

(9) Bibliography:

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(10) Appendices: None